Metal Abundances in the ICM as a Diagnostics of the Cluster History

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Abstract

Galaxy clusters with a dense cooling core exhibit a central increase in the metallicity of the intracluster medium. Recent XMM-Newton studies with detailed results on the relative abundances of several heavy elements show that the high central abundances are mostly due to the contribution from supernovae type Ia. The dominant source is the stellar population of the central cluster galaxy.

With this identification of the origin of heavy elements and the observed rates of SN Ia in elliptical galaxies, the central abundance peak can be used as a diagnostic for the history of the cluster core region. We find for four nearby cooling core clusters that the enrichment times for the central peaks are larger than 6 - 10 Gyrs even for a higher SN Ia rate in the past. This points to an old age and a relatively quiet history of these cluster core regions.

A detailed analysis of the element abundance ratios provides evidence that the SN Ia yields in the central cluster galaxies are more rich in intermediate mass elements, like Si and S, compared to the SN Ia models used to explain the heavy element enrichment in our Galaxy.

Key words: Galaxy Clusters (98.65.Cw) – Elliptical galaxies (98.54.Ew) – Abundances, chemical composition (97.10.Tk)

1 Introduction

Our understanding of the complex physics prevailing in cooling cores in clusters of galaxies is mostly driven by observation rather than by theory. It was for example the large amount of X-ray radiation detected from cluster cores that led to the scenario of cooling flows (e.g. Fabian & Nulsen 1977, Fabian 1994). And it was later again observations by XMM-Newton showing that no

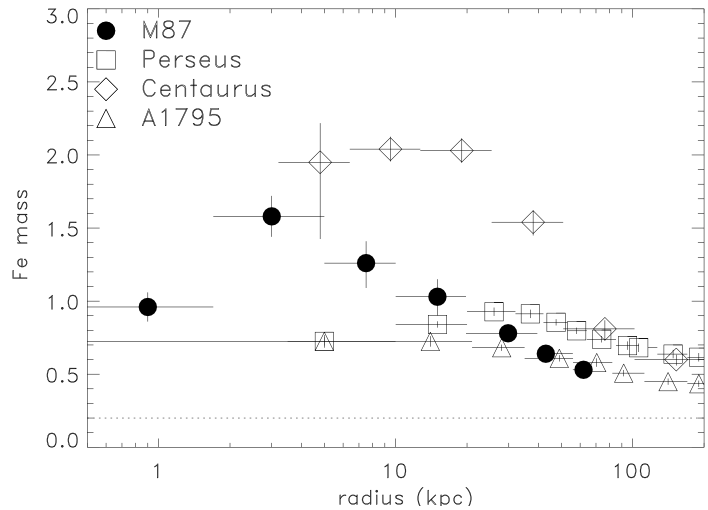

Fig. 1. Relative abundance of Fe in the ICM as a function of cluster radius in four nearby clusters (identified by the four different symbols) as deduced from XMM-Newton observations (Böhringer et al. 2004). The dashed line shows the Fe abundance value of 0.2 solar, which is observed at large radii in clusters.

steadily cooling gas is observed and by Chandra displaying interaction effects of central AGN with the cooling core plasma which lead to major revision of the physical model of cluster cooling cores with much smaller mass deposition rates than inferred previously (e.g. Peterson et al. 2001, Matsushita et al. 2002, McNamara et al. 2000, Forman et al. 2004, Churazov et al. 2000, 2001, Böhringer et al. 2002). To understand in detail the interaction effects of the central AGN with the ICM and how the ICM is heated in a globally homogeneous and fine tuned way is even more complicated. We have to hope again to exploit further observational effects to guide our interpretation. In this context the entropy distribution and the distribution of heavy elements in the ICM provide another important diagnostic tool to learn more about the energy recycling and transport processes in the central ICM. This conference contribution will concentrate on the abundance distributions as diagnostics.

To model the observed abundance distribution of heavy elements we need to know three things: the sources, the time scales, and the transport processes that redistribute the ICM.

2 The origin of the observed abundance distributions

We know two sources for the enrichment of the ICM with heavy elements: core collapse supernovae, type II, which produce a broad spectrum of element masses with a bias towards the lighter elements like O and Mg, and type Ia supernovae, thermonuclear explosions of white dwarfs, which dominantly

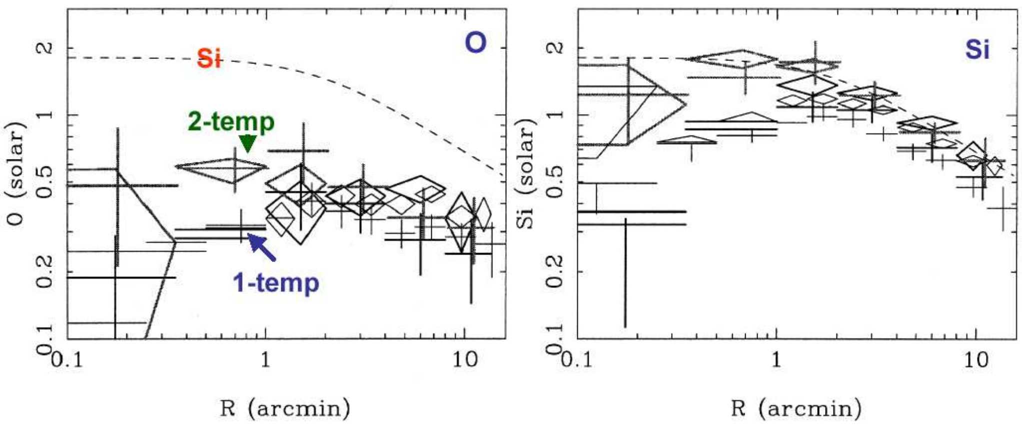

Fig. 2. Abundance profiles of O and Si in the X-ray halo of M87 in the Virgo cluster as deduced from XMM-Newton observations (Matsushita et al. 2003). The upper curves for the two-temperature model give the more realistic results.

yield Fe group elements and lighter elements like Si and S but very little O and Mg. One of the characteristics of cooling core clusters is the central abundance peak of Fe and the heavier elements (e.g. DeGrandi & Molendi 2001) as shown in Fig. 1. A more detailed inspection which elements follow this abundance peak shows that it is traced by the heavier SN Ia products but not by the lighter elements like O and Mg (Fig.2, Matsushita et al. 2003). This is consistent with the picture that SN II activity happens in the early history of cluster formation when the stellar populations of the cluster galaxies are still young. These elements have time to mix well in the ICM and show a more homogeneous distribution. SN Ia are still occuring and observed in the present day cluster ellipticals and in the central cD galaxies. The more recent yields obviously lead to more local enrichments. In particular the massive stellar population of the cD galaxies dominating the centers of cooling core clusters are responsible for the central enrichment.

An even more careful inspection of the central abundances reveals also slight increases in the relative abundances of O and Mg as shown in Fig. 3 for the case of the Centaurus cluster (Matsushita et al. 2004). The ICM abundances of these elements are comparable to the stellar abundances which implies that the ICM in the very central region most probably reflects the stellar mass loss of the central galaxy. Consideration of the budget of the central ICM for example for the case of M87 shows that the inner 10 kpc region of the ICM, roughly the region of the scale radius of cD galaxies (or approximately half light radius), contains a gas mass of about $2 \cdot 10^9$ $M_\odot$ and an iron mass of about $6 \cdot 10^6$ $M_\odot$. Both can be replenished by stellar mass loss from M87 in about 2 - 3 Gyrs if we adopt a stellar mass loss rate of $2.5 \cdot 10^{-11} \times L_B$ (Ciotti et al. 1991) and a Fe production with a supernova rate of 0.15 SNU (Cappelaro et al. 1999). It is important, however, for this enrichment to accumulate that the gas is not cooling and condensing with the classically calculated cooling flow rates, since in this case the central ICM produced by stellar mass loss would

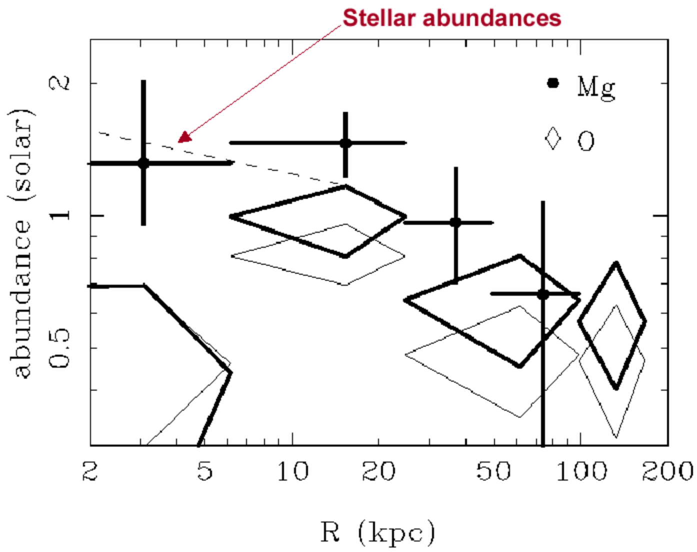

Fig. 3. Relatve abundance of O and Mg in the central ICM of the Centaurus cluster observed with XMM-Newton (Matsushita et al. 2004). The dashed line shows the stellar Mg abundance for comparison.

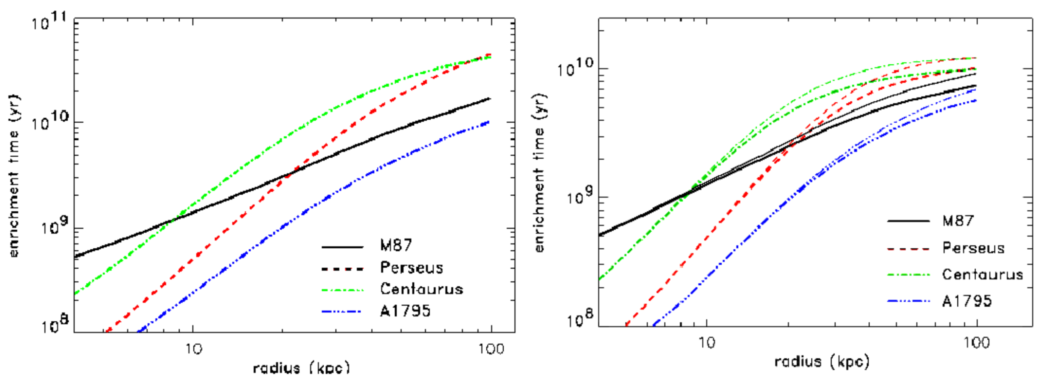

Fig. 4. Enrichment ages of the central iron abundance peak in the four galaxy clusters, M87/Virgo, Centaurus, Perseus, and A1795. The enrichment times were calculated on the basis of a SN Ia rate of 0.15 SNU (Capellaro et al. 1999) and an additional contribution by stellar mass loss. **Left panel:** with constant SN Ia rate, **Right panel:** with increasing SN Ia rate in the past described by a power law with time exponents $s = -2$ (thick lines) and $s = -1.1$. (thin lines).

disappear faster than it can be replenished. Both, the evidence described in the previous section and the observed abundances of O and Mg support the notion that the central ICM is not condensing at the high rates inferred previously within cooling flow models.

3 Enrichment times

The central abundance peak extends much further than the central 10 kpc region inside the central galaxy. Since the central galaxy dominates the stellar population out to radii of the order of 100 kpc and is therefore responsible for most of the secular heavy elements in this zone, this implies some transport of the centrally enriched ICM to larger radii and larger enrichment times than inferred above for the 10 kpc region. In Fig. 4 we show the enrichment times for the Fe abundance peak as a function of radius. The enrichment times were calculated from the total amount of excess Fe inside a given radius divided by the iron yield inferred for the integrated stellar light of the cD galaxy with the above quoted Ciotto et al. rate for stellar mass loss and the Cappelaro et al. rate supernovae type Ia with a Fe mass yield per supernove of 0.7 $M_{\odot}$ (for more details of these calculations see Böhringer et al. 2004). The excess Fe abundance is thereby determined by subtracting an ubiquitous Fe abundance of 0.15 solar believed to originate from early SII enrichment. Alternatively we were also considering the likely case that the type Ia supernova rate was higher in the past and varied with time in a power law behavior. Even for this case, where the enrichment times are shortened, we find quite large enrichment times of $5-9$ Gyrs for radii around 50 kpc and $7-12$ Gyrs for 100 kpc.

If these estimates are correct the results imply that the central regions of the clusters and their ICM can not have suffered major disturbances during these times and that the ICM experienced only mild turbulent redistribution as signified by the abundance peak which is broader than the light distribution of the central galaxy. The central regions of cooling flow clusters must be old with ages of the order of 10 Gyrs! Again, this scenario does not allow the inclusion of cooling flows with the large previously inferred mass deposition rates, since this would make the accumulation of the large observed central Fe mass excess of the order of 10^9 $M_{\odot}$ impossible. See also De Grandi et al. (2004) for a complementary discussion of the origin of the central Fe abundance from the SN yields integrated over the entire past history.

4 Supernova yields

Adopting this scenario for the enrichment of the central heavy element abundance peak, we can now study the element abundance ratio in more detail and compare the results with predictions of the supernova nucleosynthesis model calculations. The best measured abundances for the different atomic mass groups are those of Fe, Si and O. Thus we will concentrate here on the use of these elements.

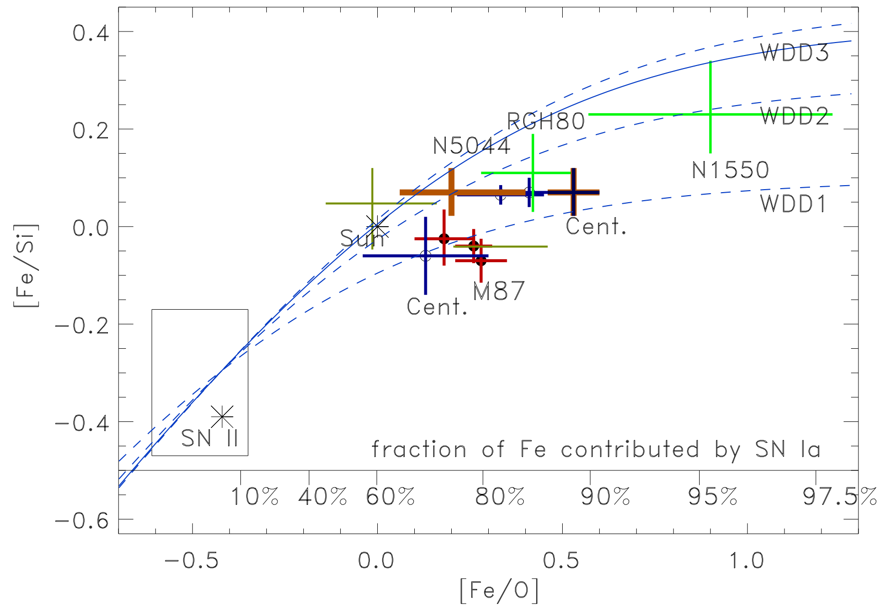

Fig. 5. Comparison of the Fe/O and Fe/Si abundance ratios for different radial regions (with $r \leq 100$ kpc, except for the left light green data point for low temperature clusters for $r = 50-200$ kpc) in different galaxy clusters with data taken from Matsushita et al. (2003 - M87; red), Matsushita et al. (2004 - Centaurus, blue), Sun et al. (2003 - NGC1550, green), Xue et al. (204 - RGH80, green), Buote et al. (2003 - NGC5044, orange thick), Tamura et al. (2004 - several cool clusters observed with XMM, light green thin), and Dupke & White (2000 - A496 observed with ASCA, blue hidden behind N5044 data points). The solid line gives the W7 model (Nomoto et al. 1984) which accounts for the abundance of our sun. The three dashed lines give the delayed deflagration models WDD1, WDD2, and WDD3 by Iwamoto et al.(1999). The lower asterisk indicates the SN II yields, the upper asterisk the composition of the Sun. The box indicates the composition of low metallicity halo stars in our galaxy (from Clementi et al. 1999). The range of observational values is well bracketed by the different theoretical SN Ia yields.

In Fig. 5 we compare the abundance ratios of Fe/O and Fe/Si in different regions in different groups and clusters of galaxies. In this diagram the Fe/O ratio is a diagnostics of the ratio of Fe yields from SN II and SNIa and the Fe/Si ratio can then be used to test various models of SN Ia yields (Matsushita et al. 2003). In the plot we have compiled the available set of observational results from XMM and Chandra (and one ASCA result) from the literature and compare them to various models with different deflagration speeds of the SN Ia explosion from Nomoto et al. (1984) and Iwamoto et al. (1999). The models lines were calculated by mixing an increasing amount of SN Ia material with the early composition taken to be similar to the average of the low metallicity galactic halo stars (Clementini et al. 1999) which is also close to the expected SN II yields as shown in the figure. The results show that the bulk of the data lay below the curve of the W7 model which fits the solar abundance and is successfully used to describe the chemical history of our galaxy (Edvardsson

et al. 1993). The WDD1 and WDD2 models provide yields with larger Si mass fractions compared to iron than supplied by the W7 model. The data points for M87 are the most extreme in requiring a relatively large Si yield (Matsushita et al. 2003). The possible reason for this is a more incomplete nuclear burning in SN Ia explosions in older stellar populations (Finoguenov et al. 2001) which is also consistent with the observed statistically lower luminosity of SN Ia lightcurves observed in supernovae type Ia in elliptical galaxies compared to spirals (Ivanov et al. 2000).

5 Conclusions

The results presented from the analysis of a few nearby clusters studied with XMM-Newton and CHANDRA provide new clues on the dynamical history of the central regions of clusters, the transport processes in the ICM, and the nucleosynthesis yields of the two main types of supernovae. The hopefully long life of the XMM and CHANDRA observatories will allow us to extend these studies systematically to a well selected larger sample of groups and clusters of galaxies, which will finally show if the conclusions drawn in this contribution can be generalized and established with higher precision.

6 Acknowledgements

The majority of the results have been obtained with XMM-Newton, an ESA mission with instruments and contributions directly funded by ESA member States and the USA (NASA). The XMM-Newton Project is supported by the Bundesministerium für Bildung und Forschung, the Max-Planck-Society, and the Haidenhain Stiftung.

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